THE REALISTIC VERSUS THE SPHERICAL HEAD MODEL IN EEG DIPOLE SOURCE ANALYSIS IN THE PRESENCE OF NOISE

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ABSTRACT

The performance of the three-shell spherical head model versus the performance of the realistic head model is investigated when solving the inverse problem with a single dipole, in the presence of noise. This is evaluated by inspecting the average dipole location error when applying a spherical and a realistic head model, for 1000 noisy scalp potentials, originating from the same test dipole and having the same noise level. The location errors are obtained utilizing a local linearization, which is validated with a Monte Carlo simulation. For 27 electrodes, an EEG epoch of one time sample and spatially white Gaussian noise we found that the importance of the realistic head model over the spherical head model reduces by increasing the noise level. –**Keywords**: EEG dipole source analysis; Gaussian noise; realistic head

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Abstract

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The spherical head model is constructed as follows. Through the 27 electrode nodes located at the scalp surface, used in the finite di erence volume conductor model, a best-fitting sphere is constructed with a radius R. A radial projection of the electrodes on the surface of the sphere is performed to obtain the electrode coordinates on the spherical head model. The radii of the outer shell of the scalp, skull and brain are R, $\frac{85}{92}R$ and $\frac{80}{92}R$, respectively.

When applying the spherical head model, the electrode positions need to be obtained to construct the best-fitting sphere. In contrast, when applying a realistic head model, the segmented MR-image needs to be constructed, the electrode positions need to be obtained and the numerical preprocessing needs to be performed. It is clear that the latter is more demanding.

2.2. The inverse problem

The EEG presented at the input of the inverse solver, with l electrodes (27) and for a single time instant can be given by $\mathbf{V_{in}} \in \mathbb{R}^{l\times 1}$. The three location parameters and the three components of the dipole are obtained by finding the global minimum of the residual energy (RE):

$$RE = \|\mathbf{V_{in}} - \mathbf{V_{model}}\|^{\mathbf{2}},$$

with $\mathbf{V_{model}} \in \mathbb{R}^{l\times 1}$ the electrode potentials obtained by the forward evaluation in the inverse problem and $\|.\|$ the L_2 norm.

The RE indicates the fraction of energy, which cannot by modeled by the dipole. The Nelder-Mead simplex method is used to find the optimal position $\mathbf{r_{opt}}$. For each dipole position the optimal components $\mathbf{d_{opt}}$ are found in the least-squares sense.

2.3. The construction of ΔR

For a given test dipole, with dipole position $\mathbf{r_0}$ and components $\mathbf{d_0}$, the forward problem is solved in a realistic head model, yielding a set of average referenced scalp potentials. From these noiseless set of potentials, noisy sets of potentials are generated by adding noise values to each of the potentials. These noise values can be described as a Gaussian with zero mean. Using the noiseless forward calculated potentials in the realistic head model, the inverse problem is solved in a spherical head model yielding dipole position $\mathbf{r_{sphere}}$ and components $\mathbf{d_{sphere}}$. A local linearization of the forward problem as presented in [10,11] with the spherical head model at these dipole parameters is then performed. This gives us the opportunity to solve for the deviations of the dipole positions $\mathbf{\Delta r^{sphere}_{noise,\,i}}$ as a function of the noise values at the electrodes. These results are obtained with a matrix multiplication, which is faster than solving the inverse problem iteratively. Furthermore, $i = 1 \ldots 1000$ corresponds with one of the 1000 noisy potential sets with noise values coming from the same distribution having a given standard deviation corresponding with a given noise level. The location error due to noise and due to the spherical head model then becomes: $\Delta r_i^{sphere} = \|\mathbf{\Delta r^{sphere}_{noise,\,i}} + \mathbf{r_{sphere}} - \mathbf{r_0}\|$, where $\|\cdot\|$ is the Euclidian norm. For a 1000 noisy potentials sets, we obtain the average location error $E(\Delta r_i^{sphere})$. Next we calculate the deviation of the dipole coordinated Δr_i^{real}, utilizing a realistic head model and due to noise. Notice that we assume that the inverse solver, applying the realistic head model, is an unbiased estimator. A local linearization of the forward problem with the realistic head model at the test dipole position $\mathbf{r_0}$ and orientation $\mathbf{d_0}$, is then performed. The location error due to noise then becomes: $\Delta r_i^{real} = \|\mathbf{\Delta r^{real}_{noise,\,i}}\|$, where $\mathbf{\Delta r^{real}_{noise,\,i}}$ is the deviation from the test dipole position for given noise values. For the same 1000 noisy potential sets as in the spherical head model case we then calculate the average location error, $E(\Delta r_i^{real})$.

When $E(\Delta r_i^{sphere})$ is much larger than $E(\Delta r_i^{real})$, for a certain noise level, then it is worthwhile using the more e ort demanding realistic head model instead of the spherical head model. On the other hand, when $E(\Delta r_i^{sphere})$ has about the same value as $E(\Delta r_i^{real})$, then it does not matter whether a realistic or a spherical head is used. Therefore, the di erence between the two average location errors $\Delta R = E(\Delta r_i^{sphere}) - E(\Delta r_i^{real})$ is introduced. We suggest that a ΔR smaller than 5 mm indicates that for a given dipole and for a given noise level both models, the spherical and the realistic head model perform equally. On the other hand when ΔR is larger than 5 mm for a given dipole and for a given noise level we argue that in this case the realistic head model performs better than the spherical model.

2.4. Validation of the linearization

A first simulation is carried out to evaluated the local linearization for one test dipole. We have calculated $E(\Delta r_i^{sphere})$ and $E(\Delta r_i^{real})$ for a number of noise levels and for 1000 noisy potential distributions, utilizing the local linearization. On the other hand we have calculated, for the same noisy scalp potentials, the inverse problem in a spherical and realistic head model. This approach is often called a Monte-Carlo simulation. The average location errors are derived and compared with the ones found utilizing the local linearization.

2.5. ΔR for 27 electrodes and Gaussian noise

In the second simulation, 427 test dipole positions, located in a coronal slice containing the vertex electrode 'Cz', are used. For each test position a dipole along the x-, y-, and z-axis is generated yielding 1281 test dipoles. The x-axis is oriented from the left towards the right ear, the y-axis is oriented from the back of the head towards the nose, and the z-axis is oriented from the bottom of the head towards the vertex electrode 'Cz'.

Further more the grand average over 1281 dipoles of ΔR, represented by $A(\Delta R)$, is also given as a function of the noise level. Notice that $A(\cdot)$ calculate the average for all test dipoles while $E(\cdot)$ calculates the average for all noisy potential distributions associated with one test dipole.

To have a more quantitative measure for a given noise level, the number of test dipoles are counted which have a ΔR larger than the chosen 5 mm. This gives us the opportunity to investigate, for a given noise level and for a large number of test dipoles, whether it is still worthwhile utilizing the more computational demanding realistic head model, instead of the spherical head model.

3. RESULTS

3.1. Validation of the local linearization

The results obtained with the local linearization are validated utilizing Monte Carlo simulations for one test dipole. The solid line in figure 1 presents the average dipole location error $E(\Delta r_i^{real})$ obtained with a local linearization of the forward problem with thed nic theadhodels, ai(on)]KHn]2IPk]3]32K

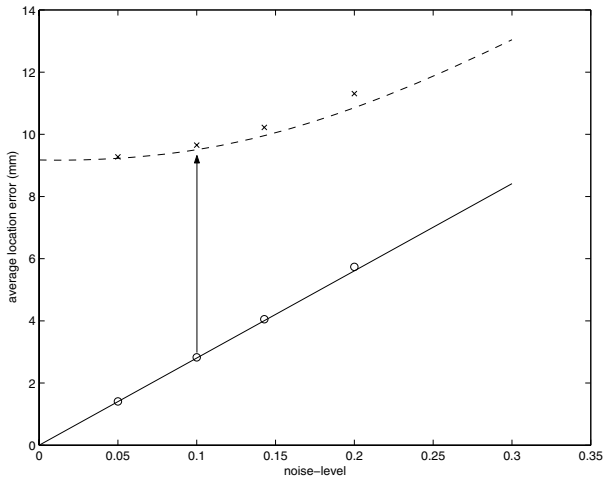

Figure 1. The solid line (-) and the dashed line (- -), depict the average dipole location error as a function of the noise level obtained with the local linearization of the forward function when utilizing a realistic and spherical head model, respectively. The ($\circ$) and ($\times$) present the average dipole location errors obtained with a Monte-Carlo simulation, for noise levels 0.2, 0.14, 0.1, and 0.05, utilizing the realistic and spherical head model, respectively. The difference between the average location error obtained with the spherical and realistic head model or ΔR for the noise level of 0.1 is illustrated with the arrow.

an average location error. The '$\circ$' depicts the average location error obtained from a Monte-Carlo simulation for the noise levels 0.05, 0.1, 0.14 and 0.2, utilizing the realistic head model. The '$\times$' depicts the average location error obtained from a Monte-Carlo simulation, utilizing a spherical model. One can notice that the average location errors obtained with the Monte-Carlo simulation correspond well with the values obtained through local linearization, and this even for larger noise levels. The $\Delta R = E(\Delta r_i^{sphere}) - E(\Delta r_i^{real})$, for noise level 0.1, is marked with the arrow in figure 1. It can also be observed that by increasing the noise level the value of ΔR decreases.

3.2. ΔR for 27 electrodes and Gaussian noise

The first, second, third and fourth row in figure 2 present the value $\Delta R = E(\Delta r_i^{sphere}) - E(\Delta r_i^{real})$ for a noise level equal to 0, 0.05, 0.1 and 0.2, respectively as a function of the dipole position. The dipole orientation is along the x-axis. A contour with ΔR equal to 5 mm is also given. For noise level zero ΔR equals $E(\Delta r_i^{sphere})$. By increasing the noise level, the ΔR values decrease for all test dipoles. Hence the areas where ΔR is larger than 5 mm decrease when increasing the noise level.

The grand average over all the test dipole positions of ΔR is presented in the column marked with A(ΔR) in table 1. It can be observed that by increasing the noise level the grand average of ΔR, decreases from 5.5 mm to 1.8 mm.

In table 1, the percentage of ΔR values larger than 5 mm are also given, for the applied noise levels. Notice that 60% of the test dipole have a ΔR larger than 5 mm for the noiseless case. Evoked potentials and epileptic spikes coming from the same focal source are often averaged, to reduce the background EEG. For the averaged spikes the noise level is typical situated around 0.1. For this noise level 13.4% of the test dipoles have a ΔR larger than 5 mm. This number decreases

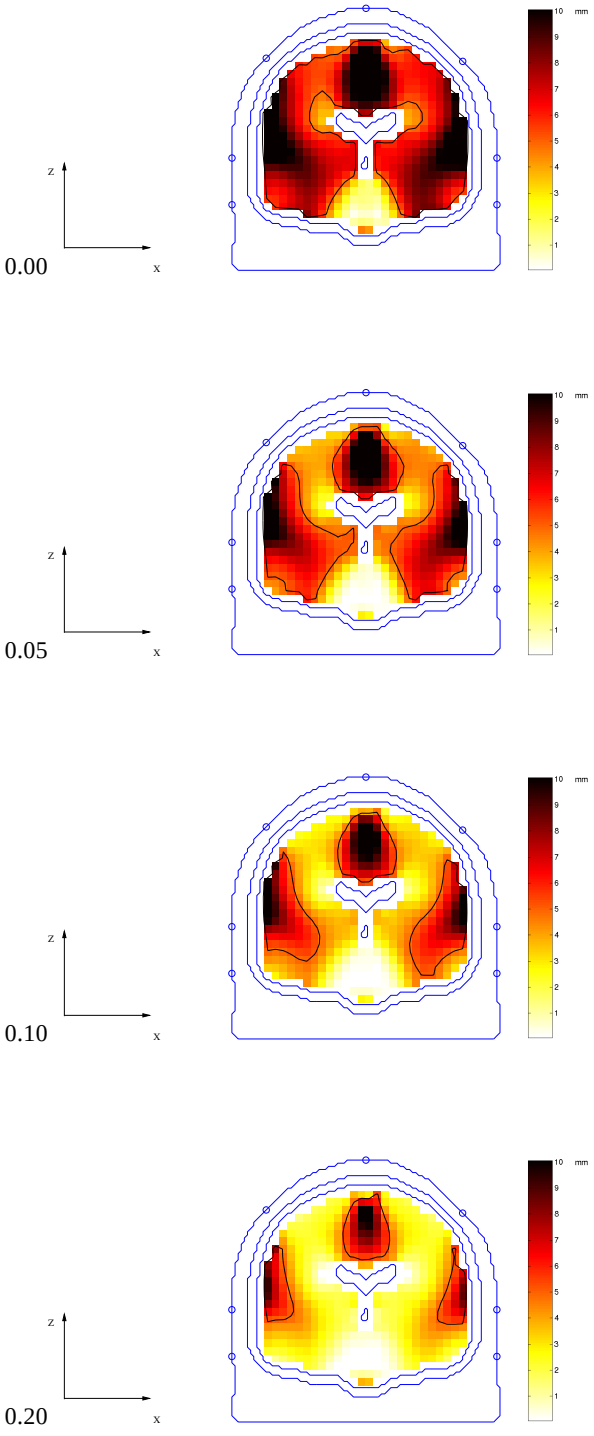

Figure 2. The first, second, third and fourth row illustrate $\Delta R = E(\Delta r_i^{sphere}) - E(\Delta r_i^{real})$ for noise levels equal to 0, 0.05, 0.1 and 0.2, respectively. A contour with ΔR equal to 5 mm is also given. The configuration with 27 electrodes and Gaussian noise is used. The results for dipoles oriented along the x-axis are depicted.

Table 1. The grand average over the 1281 test dipole for ΔR,is presented. Further more, the relative number of test dipoles yielding a ΔR larger than 5 mm, is also given. The noise levels 0, 0.05, 0.1 and 0.2 are considered. 27 electrodes, and Gaussian noise is applied.

noise level	SNR	A(ΔR)(mm)	$\sharp(\Delta R > 5\ mm)(\ \%\ )$
0.0	∞	5.5	60.0
0.05	20	4.0	25.5
0.1	10	3.1	13.4
0.2	5	1.8	7.6

to 7.6% for a noise level of 0.2, which corresponds with an unaverage epileptic spike. The higher the noise level, the less important becomes the usage of the realistic head model over the spherical head model.

4. CONCLUSION

The aim of this paper was to evaluate the performance of the three-shell spherical head model versus the performance of the realistic head model, in solving the inverse problem with a single dipole in the presence of noise. In our simulations, the average location errors $E(\Delta r_i^{sphere})$ and $E(\Delta r_i^{real})$ are obtained through a local linearization. As control we found for one dipole that the values of $E(\Delta r_i^{sphere})$ and $E(\Delta r_i^{real})$ obtained through local linearization are in good agreement with the ones obtained when utilizing a Monte Carlo approach. When utilizing 27 electrodes, an epoch of one time sample and Gaussian noise, it was found that by increasing the noise level from 0 to 0.2, that the grand average over all the test dipoles of ΔR decreased from 5.5mm to 1.8mm, respectively. For a noise level of 0.1, corresponding with an averaged epileptic spike, 13.4% of the test dipoles have a ΔR larger than 5mm. For a noise level of 0.2, corresponding with an unaveraged epileptic spike, less than 10 % of the test dipoles have a ΔR larger than 5mm. The importance of the realistic head model over the spherical head model reduces by increasing the noise level.

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